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ABSTRACT

A partial wave analysis and a Dalitz plot analysis of high-statistics data from reaction $\pi^- p \to K^+ K_S \pi^- n$ at 8.0 GeV/c show that the D(1285) is a $J^{PG} = 1^{++}$ state and the E(1420) a $J^{PG} = 0^{-+}$ state both with a substantial $\delta\pi$ decay mode. The 1^{++} $K^*\bar{K}$ wave exhibits a rapid rise near threshold but no evidence of a resonance in the E region. The assignment of $J^{PG} = 0^{-+}$ to the E is confirmed from a Dalitz-plot analysis of the reaction $pp \to K^+ K_S \pi^- X^\circ$.

Since the observation that the J/ψ has a substantial radiative decay to the i(1440) making it a prime glueball candidate[1] there has been renewed interest in the spin-parity of the E(1420). The E(1420) was originally discovered by Armenteros et al.[2] in pp annihilations at rest with a preferred J^{PG} assignment of 0^{-+}. However, a subsequent experiment by Dionisi et al.[3] concluded, from a Dalitz plot analysis of the reaction $\pi^- p \to K^+ K_S \pi^- n$ at 4.2 GeV/c, that the E(1420) is a 1^{++} state coupling predominantly to K^*K. This conclusion was supported by the higher statistics experiment of Armstrong et al.[4] by a similar analysis of central production of the E(1420). Our Dalitz plot analysis of the $K^+ K_S \pi^-$ system in the reaction

$$\pi^- p \rightarrow K^+ K_S \pi^- n \text{ at } 8.0 \text{ GeV/c.} \qquad (1)$$

with more then 10 times the statistics of Dionisi et.al. contradicts the two latter claims and concludes that the E(1420) is a 0^{-+} state[5]. We will present here, in addition to our original results, a partial wave analysis (PWA) of the same data and a Dalitz plot analysis of the reaction

$$\bar{p}p \rightarrow K^+ K_S \pi^- X^0 \text{ at } 6.6 \text{ GeV/c.} \qquad (2)$$

They all support our conclusion that the E(1420) is a $J^{PG} = 0^{-+}$ state.

The data come from two experiments performed with the Brookhaven National Laboratory Multiparticle Spectrometer (MPS). The layout is described in ref. 5 for the experiment with a beam at 8.0 GeV/c. It consists basically of a tagged beam impinging on liquid-hydrogen target located inside the MPS magnet and surrounded on four sides by a lead-scintillator veto box. Downstream of the target but still inside the magnet are seven drift-chamber modules with seven measuring planes each. Interspersed with the drift-chamber modules are three proportional wire chambers (P1, P2, P3) for triggering purposes. Downstream of the magnet there is a large high-pressure Cherenkov counter hodoscope (C1) with γ threshold = 10 and two scintillation counter hodoscope (H1, H2). The only difference in the apparatus between the two runs was the use of a 60-cm target for $\bar{p}$ instead of a 30-cm target for π^-.

The trigger required a positive particle with momentum > 1.5 GeV/c going through C1, H1 and H2 without emitting light in C1. This was achieved using a RAM-trigger, a three dimensional coincidence matrix system using random-access memories (RAM's). There were actually two RAM's in coincidence, one using P2*P3*H2 for momentum selection and another using P2*P3*(H1*$\bar{C}$1) for nonpion identification. For the π^- beam run we required in addition a multiplicity of 2 in P1, 4 in P2 and no signal in the veto box.

For the $\bar{p}$ beam run the only requirements beyond the RAM's were a multiplicity of at least 2 in P1 and at least 4 in P2. The beam fluxes were 10^6/pulse for π^- and 10^5/pulse for $\bar{p}$, and the trigger rates 10/pulse and 20/pulse respectively (with about 1500 pulses/hour). The total number of triggers accumulated were $1.5*10^6$ for a 200-hour π^- run and $4.5*10^6$ for a 350-hour $\bar{p}$ run. The total number of events for reaction (2) is 16,000 and for reaction (1) 15,000 after requiring the missing-mass squared to be between 0.4 and 1.3 (GeV) and -t to be less than 1.0 (GeV).

The $K^+K_S\pi^-$ mass spectra, given in Figs. 1a and 1b, show clearly the D and E states. The background in reaction (2) is much higher than for reaction (1), in part because we do not separate K^+ and p and we expect reaction (2) to be contaminated by $\bar{p}pK_S$ events. The missing-mass squared for reaction (2) is featureless and the t distribution is flat, consistent with production by annihilation in flight. A fit to the spectra with two simple Breit-Wigner functions and a polynomial function give for reaction (1): m_D =1285 $\pm$ 2MeV and Γ_D = 22 $\pm$ 2 MeV; m_E = 1421 $\pm$2 MeV and Γ_E =60 $\pm$ 10 MeV,
and for reaction (2):
m_D =1277 $\pm$ 3 MeV and Γ_D =32 $\pm$ 8 MeV; m_E =1424 $\pm$ 3 MeV and Γ_E =70 $\pm$ 15 MeV.

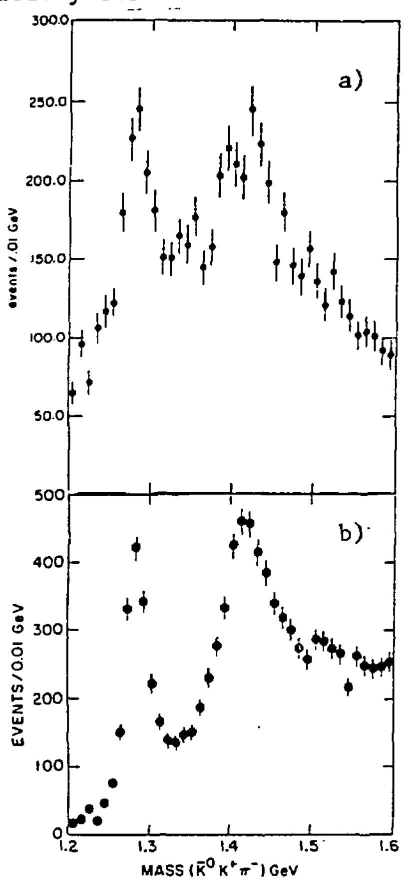


Fig. 1a. Effective mass spectrum for reaction (2).
Fig. 1b. Same as 1a) for reaction (1) requiring $0.4<MM^2<1.3$ $(GeV)^2$, $0.48<M(K_S)<0.52$ GeV and $-t <1.0$ $(GeV)^2$.

The above values are consistent with those observed in other hardronic reactions.

For reaction (1) we have performed a complete partial wave analysis with amplitudes that depend on a set of five variables, to be denoted τ: three Euler angles (α, β, γ) which rotate from the Gottfried-Jackson frame to the Dalitz system and two Dalitz-plot variables (s_1, s_2). The differential cross section is given by:

$$I(\tau) \equiv \frac{d\sigma}{d\alpha d\beta d\gamma ds_1 ds_2} \propto \sum \rho_{ab} A_a A^*_b \tag{3}$$

where a,b are the set of quantum numbers needed to describe the production and decay, i.e. $a = (J^{PG}M^{\eta}$ (isobar)). We have assumed for the analysis that only two isobar states are needed, K^* and δ. Since the recoil baryon has spin 1/2 the density matrix is constrained to have rank ≤ 2 for a given t bin. This constraint plus the positivity of the density matrix can be imposed by requiring that:[6]

$$\rho_{ab} = \sum_{k=1,2} V_{ak} V^*_{bk} \tag{4}$$

where V_{ak} are complex parameters in the fit.

From threshold to 1.6 GeV we found that only the states $J = 0^{-+}, 1^{++}, 1^{+-}, 1^{-+}$ with all allowed M^{η} values and incoherent background were needed to fit the data. The decay modes $\delta\pi$ and $K^*\bar{K}$ are allowed for 0^{-+} and 1^{++}, while for 1^{+-} and 1^{-+} only the $K^*\bar{K}$ mode is allowed. The total number of parameters in the partial wave analysis is of the order of 30, compared to ≈ 10 for a Dalitz-plot fit, but the PWA deals with a 5-dimensional space instead of 2-dimensional [illegible] for the Dalitz-plot analysis.

The analysis was [illegible] ng MINUIT[7] and a program developed at BNL[8] tc [illegible] maximum likelihood with the log of likelihood given by:

$$L = \sum_{i=1}^{n} \ln \frac{I(\tau_i)}{\int I(\tau) A(\tau) d\tau} \tag{5}$$

where A(τ) represents the finite acceptance of our apparatus. The results are displayed in Fig. 2, where the different J^{PG} waves are displayed as a function of $K\bar{K}\pi$ mass. We chose to show only the summed partial waves (over M^{η} and decay modes) because we found that the separation between decay modes depends sensitively on the δ parameterization while the sum is more stable. The δ parameterizations we used is the coupled channel formula of Flatté, following previous analyses. We have used alternative parameterizations (such as an S-wave Breit-Wigner) and found that the results shown in Fig. 2 did not vary significantly.

As can be seen in Fig. 2 the 1^{++} wave shows a peak in the D-region and a rapid rise across the $K^*\bar{K}$ threshold in the E-region. This confirms that the D is 1^{++} state but not the E. On the other hand the 0^{-+} wave shows a clear and significant peak in the E-region.

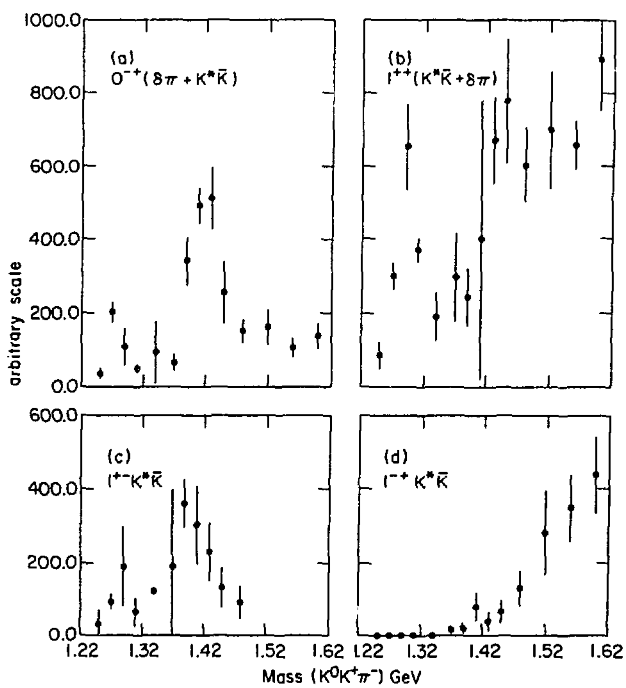
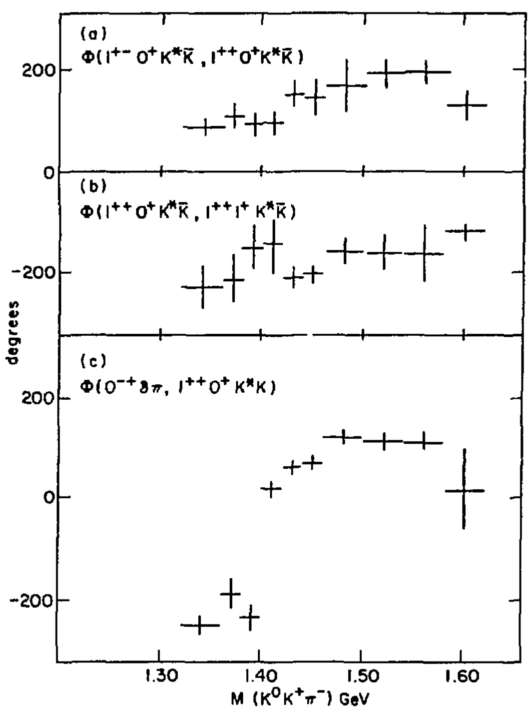


Fig. 2 Acceptance corrected partial waves for reaction (1) obtained by a PWA.
a) $J^{PG} = 0^{-+}$ wave adding $\delta\pi$ and $K^*\bar{K}$ contributions
b) $J^{PG} = 1^{++}$
c) $J^{PG} = 1^{+-}$ wave

In Fig. 3 we show the relative phases. The rapid positive increases increase of the $0^{-+}(\delta)$ phase relative to the $1^{++}0^{+}(K^{*}\bar{K})$ phase is characteristic of a 0^{-+} resonance interfering with a non-resonant 1^{++} background. The $1^{+-}(K^{*}\bar{K})$ shows some peaking in that region, however, there is no noticeable phase motion respect to the 1^{++} wave (Fig. 5a), so it is probably not resonating. The other waves in the fit, 1^{-+} and incoherent backgound (not shown), are negligible below 1.4 GeV and rise slowly up to 1.6 GeV. This analysis supports the original conclusion from a Dalitz-plot analysis of the same data that the D is a 1^{++} state and the E a 0^{-+} state with no evidence for a $1^{++}(K^{*}\bar{K})$ state in the E-region. For comparison we show in Fig. 4 the results of the Dalitz-plot



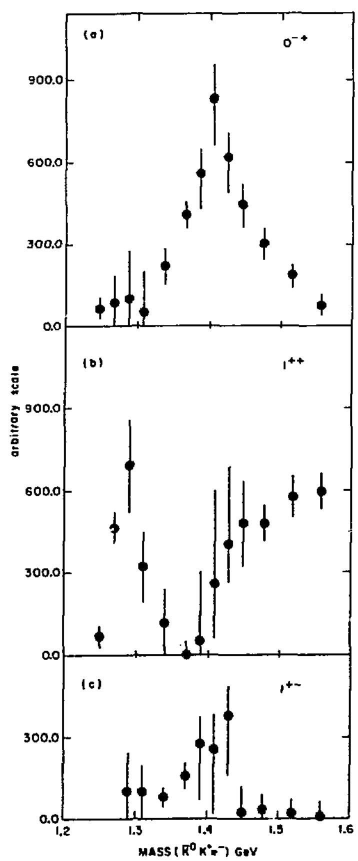


Fig. 3 Relative phases a function of $K\bar{K}\pi$ mass. The notation is J^{PG} (isobar).

Fig. 4 Spin-parity content of $K\bar{K}\pi$ system produced in reaction (1).

analysis using Zemach amplitudes. Although there are some quantitative differences between the two sets of results (not surprising given the very different parameterizations), the conclusions to be drawn are identical.

For reaction (2) a partial wave analysis is not likely to add any more information than a Dalitz-plot analysis since it is an inclusive annihilation channel with very little production information. Therefore only a Dalitz-plot analysis with Zemach amplitudes was done. The partial waves between 1.36 and 1.52 GeV are given in Fig. 5. The large amount of background in the D-region makes it impossible to separate $1^{++}(\delta)$ from $0^{-+}(\delta)$. In the E-region we found that the only required waves were 0^{-+}, 1^{++}, 1^{+-} and a flat phase space background. The analysis supports the conclusion that the E is a 0^{-+} state.

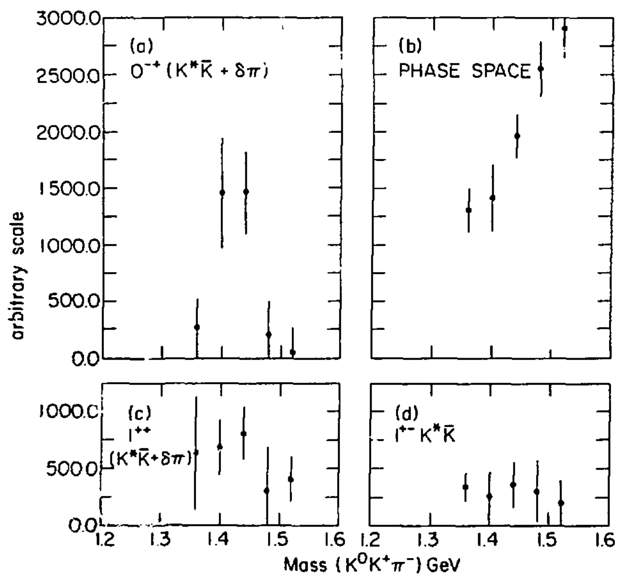


Fig.5
Spin parity content of $K\bar{K}\pi$ system in reaction (2).

In Table I we show the difference in likelihood for various hypothesis (a similar table is given in ref. 5 for reactions (1)). Note that if we had done the fits one wave at a time with a flat background we could have erroneously concluded that the data favored a 1^{++} interpretation for the E.

Table I. Differences in Log of Likelihood from Best Fit (0^{-+}, 1^{++},1^{+-} and Background)

Waves in fit*	1.38-1.42 GeV	1.42-1.46 GeV
1^{++},1^{+-}	-10	-7.
1^{++}	-20	-25.
0^{-+}	-25	-38.

*All fits include flat phase space background.

In summary, we conclude that the D(1285) is a 1^{++} state and the E(1420) is a 0^{-+} state, and both of them require substantial $\delta\pi$ decay modes. We do not quote at this time a $K^*K/\delta\pi$ branching ratio as its value depends on the precise parameterization of the δ and is subject to a large systematic error. The 1^{++} ($K^*\bar{K}$) wave does not show a resonant behaviour in the E-region rather, in reaction (1), shows a rapid rise near threshold. Our results contradict those of Dionisi, et al.[3] and Armstrong, et al.[4] who find the E is a 1^{++} ($K^*\bar{K}$) state. They are in good agreement with those of Baillon and of the J/ψ radiative decay,[11] so that the i(1440) and the E(1420) may very well be the same object, weakening the glueball interpretation for the ı(1440). However, the recently measured values for the ı(1440), M= 1458 ± 7 and = 99 ± 6 MeV in J/ψ decays, are higher than those of the hadro-produced E(1420), so the question cannot be considered settled.[11]

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